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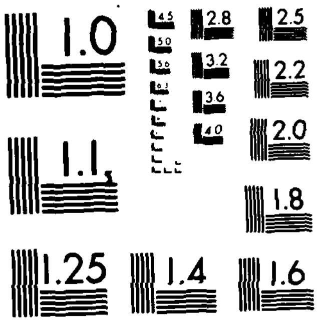

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LECTURES ON MATHEMATICAL COMBUSTION

Lecture 4: SVFs and NEFs

Technical Report No. 149

J.D. Buckmaster & G.S.S. Ludford

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Theoretical and Applied Mechanics

Thurston Hall

Ithaca, New York

LECTURES ON MATHEMATICAL COMBUSTION

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Contents

Lecture 4

SVFs and NEFs

For want of a complete analysis of multidimensional flows in pre-asymptotic days, it was natural to try to identify special characteristics that play particularly important roles in the understanding of flame behavior. Flame speed and temperature are examples of such characteristics that have already been identified; a more subtle characteristic, introduced by Karlovitz, is flame stretch. We shall start by discussing this concept, so as to have it available when the later analysis is reached.

1. Flame Stretch

To define this (or for that matter flame speed) in an unambiguous fashion, we must first define a flame surface, i.e. a surface characterizing the location of the reaction. For large activation energy the reaction zone is such a surface when viewed on the scale of the preheat zone, since it then collapses into the flame sheet. If the flame can be viewed as a hydrodynamic discontinuity, as in section 3.1, then the discontinuity itself is a flame surface. In either case, a flow velocity is defined on each side of the surface, such that $\underset{\sim}{v}_{\perp}$ is continuous across the surface.

Consider a point that remains on the (moving) flame surface but travels along it with the velocity $\underset{\sim}{v}_{\perp}$. The set of such points forming a surface element of area S will, in general, be deformed by the motion, so that S will vary with time (figure 1). If S increases, the flame is said to be stretched; if S decreases, the flame experiences negative stretch and is said to be compressed. A measure of the stretch is the proportionate rate of change

$$K \equiv S^{-1} dS/dt, \tag{1}$$

known as the Karlovitz stretch. Note that d/dt is not a material derivative; the fluid particles in the surface element change. The points advance with the flame surface, i.e. at the speed V and not v_n.

The deformation of the surface element consists of two parts corresponding to the motions with speed V along the normal and with velocity $\underset{\sim}{v}_\perp$ tangentially. The first, known as dilatational stretch, is found to be κV, where κ is the first (or mean) curvature of the surface, taken positive when the surface is concave towards the burnt gas; the other, known as extensional stretch, is $\underset{\sim}{\nabla}_\perp \cdot \underset{\sim}{v}_p$, where $\underset{\sim}{v}_p$ is the tangential component of velocity at neighboring points projected onto the tangent plane at the point of interest. Since

$$\underset{\sim}{\nabla}_\perp \cdot \underset{\sim}{v}_p = \underset{\sim}{\nabla}_\perp \cdot \underset{\sim}{v}_\perp + \kappa v_n, \tag{2}$$

the Karlovitz stretch is

$$K = \underset{\sim}{\nabla}_\perp \cdot \underset{\sim}{v}_\perp + \kappa W \quad \text{with} \quad W = V + v_n. \tag{3}$$

Thickness is another concept characterizing a flame that can be treated as a hydrodynamic discontinuity. In section 3.1 the nominal thickness $5\lambda/c_p M_r$ was introduced, but here we need a local, instantaneous definition. It is natural to replace M_r with M, and this is found to be appropriate: decay of the temperature in the preheat zone takes place over distances proportional to M^{-1} (cf. equation (3.25)). In turn $M = \rho W$ may be replaced by W, since the flow is incompressible on either side of the surface.

Introduction of the notion of thickness leads to the concept of flame volume generated by a surface element of a hydrodynamic discontinuity; this is proportional to

$$\Delta = S/W. \tag{4}$$

Just as changes in surface element led to the concept of Karlovitz stretch, so changes in volume lead to the voluminal stretch

$$B \equiv \Delta^{-1}d\Delta/dt = K-W^{-1}dW/dt \tag{5}$$

introduced by Buckmaster. The stretch B arises naturally in our consideration of SVFs, to which we turn next.

2. The Basic Equation for SVFs

The discussion now focuses on the combustion field, i.e. the internal structure of the discontinuity. To confine attention to changes that occur over times and distances $O(\theta)$, we make the transformation

$$(y,z,t) = \theta(\eta,\zeta,\tau). \tag{6}$$

Correct to $O(\theta^{-1})$, the governing equations (3.14) reduce once more to the form (3.21), since the second derivatives $\partial^2/\partial y^2$ and $\partial^2/\partial z^2$ become $O(\theta^{-2})$ under this transformation. As a consequence, the results (3.25,26) are still valid provided ϕ_* is allowed to depend on η,ζ as well as τ. Of course V does likewise (in spite of the apparent contraction (3.37)).

One relation between V and ϕ_* is given by the universal result (3.27). The second comes from the generalization (3.39) of the enthalpy balance used in section 3.3. Comparison of the balances (3.28) and (3.39) shows that we have to deal with just one new term, namely

$$\int_{-\infty}^{0+} \nabla^2(T+L^{-1}Y)dn; \tag{7}$$

and the continued validity of the formulas (3.25,26) ensures that the evaluations of corresponding terms in the two balances are the same. At first glance the term (7) appears to be $O(\theta^{-2})$, and hence negligible, because the operator $\nabla_\perp$ is $O(\theta^{-1})$. It is important to realize, however,

that T, Y are given by the formlas (3.25,26) only when n has its local meaning. The curvature of the flame sheet, from which n is measured, thereby provides a contribution $-\theta^{-1}\kappa\partial/\partial n$ to $\nabla_\perp^2$, so that the term (7) becomes

$$-\theta^{-1}\kappa(T_b-T_f-\mathcal{L}^{-1}Y_f) = \theta^{-1}\kappa(\mathcal{L}^{-1}-1)Y_f; \tag{8}$$

here κ is the θ-multiplied first curvature of the flame sheet. The second relation between ϕ_* and V is therefore

$$\phi_* = \Psi V^{-2} - bV^{-3}\dot{V} + bV^{-1}\kappa, \tag{9}$$

which should be compared with the plane result (3.29).

Elimination of ϕ_* between the two relations now gives the basic equation

$$b(\dot{V}-V^2\kappa) = V^3 \ell n V^2 + \Psi V \tag{10}$$

of an SVF, which should be compared with the plane result (3.31). It can be recast in terms of the stretch concepts introduced in section 1 by noting that

$$W = V, \quad K = \kappa V \tag{11}$$

for the stagnant flow (3.13) on which our analysis has been based. Thus,

$$b(W^{-1}dW/d\tau - K) \equiv -bB = W^2 \ell n W^2 + \Psi, \tag{12}$$

where K and B, the proportionate rates of change in surface and volume elements, are measured on the slow time scale τ (just as κ is measured on the $O(\theta)$ distance scale), and b has the definition (3.29a). In this form, the equation is valid for an arbitrary flow field, not just the stagnant one that we have considered for the sake of simplicity. (The

superficial stretch is then purely dilatational.) When the constant-density approximation is abandoned there are two modifications or, rather, reinterpretations. The parameter b becomes a more complicated function of L, but still has the property (3.32). In addition, the equation is only valid for the hydronamic discontinuity, not for the flame sheet; here it is valid for either, because the velocity field does not change through the flame. (When change in density is taken into account, W must be evaluated ahead of the discontinuity, as is customary.)

The basic equation (12) for SVFs does not, in general, determine the wave speed W directly; it is a (complicated) partial differential equation for the shape of the moving surface. Only for $L = 1$ (i.e. $b = 0$) does it reduce to an equation for W; in particular, $W = 1$ in the absence of heat loss. For plane deflagrations, there is no superficial stretch ($K = 0$) but there is voluminal stretch ($B = -V^{-1}\dot{V}$), due to changes in flame thickness, and equation (3.31) can be interpreted in terms of it.

3. The Effect of Stretch on SVFs

We have introduced the concept of stretch because of the importance attached to it in the past thirty years. Far-reaching use has been made of it as an intuitive tool in the prediction and explanation of flame behavior, particularly of quenching. In essence, the claim is that stretching a flame causes it to decelerate, and stretching it too much will extinguish it. While the claim has matured with time, its essence persists. However, until SVFs were identified and their connection with stretch discovered, the claim was no more than conjecture: now we can deduce the effect of stretch on flame speed from the basic equation (12), at least for SVFs. More about stretch, in the context of NEFs, will appear in section 10.5.

To be sure, the stretch involved in equation (12) is B and not K; but, if the thickness does not vary, there is no distinction. (An example is the stagnation-point flow treated next.) Consider first adiabatic conditions, i.e. $\Psi = 0$. From figure 2, which shows a plot of $W^2 \ln W^2$ versus W^2, it is clear that, for $b > 0$ (i.e. $\mathcal{L} > 1$), positive values of B correspond to values of W less than 1, and that there is no value of W for

$$B > e^{-1}b^{-1} > 0. \tag{13}$$

The effect of stretch is indeed as conjectured, provided the Lewis number is bigger than 1. But, for a Lewis number less than 1, this is not so: for $b < 0$ ($\mathcal{L} < 1$), positive values of B correspond to values of W greater than 1, and there is no limit; the flame accelerates when stretched, and can tolerate any stretch. In fact, deceleration is associated with negative stretch (compression), of which the flame cannot tolerate too much: for

$$B < e^{-1}b^{-1} < 0, \tag{14}$$

there is no solution.

When there is heat loss, i.e. for $\Psi \neq 0$, the conditions (13,14) are replaced by

$$B \gtrless (e^{-1}-\Psi)b^{-1} \text{ accordingly as } \mathcal{L} \gtrless 1; \tag{15}$$

the heat loss helps to extinguish the stretched or compressed flame. In fact, when the loss is large enougn (namely for $\Psi > e^{-1}$) no stretch or compression is required at all, a result in accord with that for steady plane deflagrations in section 3.3. Moreover, the extinction speed $e^{-\frac{1}{2}}$ obtained there is now seen to have general validity for SVFs.

These conclusions about extinction are only of interest if it is known that stretch of the required amount (positive or negative) can be applied to a flame. It is conceivable that, when there is insufficient heat loss for extinction, the flame can always adapt to the flow conditions so as to avoid being extinguished. The stagnation-point flow considered next shows that is not so.

We add

$$\chi = x/\theta \tag{16}$$

to the slowly varying coordinates (6), and now take axes as shown in figure 3. The stagnation-point flow is then

$$\underset{\sim}{v} = \varepsilon(\chi, -\eta), \tag{17}$$

where $\varepsilon > 0$ is the rate of strain. (No confusion will result from having used ε in a different way in section 3.1.) While there is a whole family of solutions of the basic equation (12), we shall concentrate on the possibility of a stationary flat flame, located at

$$\eta = \eta_* \text{ (say).} \tag{18}$$

Assuming such a flame exists, we have

$$W = \varepsilon\eta_*, \; \kappa = 0, \; v_\perp = \varepsilon\chi, \tag{19}$$

so that its thickness is constant and

$$B = K = \partial(\varepsilon\chi)/\partial\chi = \varepsilon \tag{20}$$

according to the definition (3). The stretch, whether voluminal or superficial, is just the strain rate. We conclude from the result (15) that,

under adiabatic conditions, a stationary flat flame exists for all (positive) ε when L is less than one, but not for

$$\varepsilon > e^{-1}b^{-1} \tag{21}$$

when L is greater than one.

There is no practical difficulty to increasing ε; just the speed of the incident stream has to be raised. As the strain rate is gradually increased up to the values (21), we may expect the flame to be extinguished. Before these values are reached the flame will lie at the position (18), where η_* is given by

$$2\varepsilon\eta_*^2 \ln(\varepsilon\eta_*) + b = 0. \tag{22}$$

Under certain conditions, a rear stagnation-point flow can be established and a flame be made to lie in it (cf. section 7.6). The analogous conditions for the existence and extinction of a stationary flat flame here can be obtained by changing the sign of ε above.

-. The Basic Equations for NEFs

The NEF is characterized by the requirements (3.34) and (3.41), the second of which corresponds to using the expansions

$$T = T_0 + \theta^{-1}T_1 + \ldots, \quad Y = (H_f - T_0) + \theta^{-1}(H_1 - T_1) + \ldots. \tag{23}$$

When these assumptions are used, the basic equations (3.14) become

$$\partial T/\partial t = \nabla^2 T \quad \text{on either side of the flame sheet,} \tag{24}$$

$$\partial h/\partial t = \nabla^2 h + l\nabla^2 T \quad \text{everywhere,} \tag{25}$$

if bulk heat loss is negligible; here T stands for T_0, and H_1 has been replaced by h. Boundary and initial conditions must be consistent with the assumption that H is constant to leading order, emphasizing once more that NEFs are a restricted class of solutions.

Ahead of the flame sheet the full equations (24,25) hold; but in the burnt gas the assumption of equilibrium leads to

$$T = T_b, \; \partial h/\partial t = \nabla^2 h \tag{26}$$

there, the temperature perturbation accounting for the whole of h. The solutions on the two sides must be linked by jump conditions, to be derived next.

These conditions are deduced by analysis of the reaction-zone structure, a question that was addressed in sections 2.4,5. First, the very existence of a structure requires

$$\delta(T) = 0 \quad \text{with} \quad \delta(\;) = (\;)_{0+} - (\;)_{0-}; \tag{27}$$

then, when $\partial T/\partial n = 0$ for $n = 0+$ (as here), the structure gives

$$\partial T/\partial n\Big|_{0-} = Y_f e^{-\phi_*/2}, \tag{28}$$

where $-T_b^2\phi_*$ is the flame-temperature perturbation, i.e. the value of h at the flame sheet. The remaining jump conditions

$$\delta(h) = 0, \quad \delta(\partial h/\partial n) = \ell\partial T/\partial n\big|_{0-} \tag{29}$$

come from integrating the equation (25) through the reaction zone and matching the result with the combustion fields outside.

The equations governing NEFs have been developed under the assumption (13b), i.e. a quiescent mixture. When the mixture is in motion they must be replaced by

$$DT/Dt = \nabla^2 T, \; Dh/Dt = \nabla^2 h + \ell\nabla^2 T \tag{30}$$

ahead of the flame sheet, and

$$T = T_b, \quad Dh/Dt = \nabla^2 h \tag{31}$$

behind. The system (27-31) defines an elliptic free-boundary problem of the fourth order, with the flame sheet as the moving boundary. Solution is a formidable question, tackled in three ways that may be listed as follows:

(i) small perturbations,

(ii) numerical integration,

(iii) special geometries.

Stability considerations fall under (i); NEFs are prominent in the stability lectures 5, 6, and 7. (Unlike SVFs they are stable for certain values of the Lewis number.) The numerical work under (ii) has dealt only with a parabolic limit of the elliptic problem; some resulting Stefan problems are considers in lecture 10. An example of (iii), stagnation-point flow, is discussed in the next section, where the effect of stretch will be examined once more.

The discussion of general deflagrations started in lecture 3 with a consideration of hydrodynamic discontinuities, i.e. waves whose length scale is large compared to their thickness (as represented by the parameter ε in section 3.1). The need to know the wave speed then led to an examination of the flame structure, and the uncovering of SVFs and NEFs as classes of solutions that could be handled by the asymptotics. The SVF is an acceptable structure for the interior of the hydrodynamic discontinuity if

$$\theta = O(\varepsilon^{-1}), \tag{32}$$

since then the undulations of the flame sheet follow those of discontinuity.

No demand of the type (32) is made of NEFs; the activation energy is independently large. In other words, NEFs exist whether hydrodynamic

discontinuities do or not. If an NEF can be viewed as a hydrodynamic discontinuity it corresponds to a solution with variations on the scale ε^{-1} (other than in the n-direction). To leading order it must, therefore, be a steady, plane deflagration traveling at the adiabatic speed: $W = 1$ in the jump conditions (3.9,10,12).

NEFs are most useful when they cannot be viewed as hydrodynamic discontinuities, witness what we shall have to say about them from now on. Their power is evident in the stability considerations of lecture 5. As so often happens in truly basic research, a concept born of one question has reached its full power in circumstances where that question is meaningless. Such unpredictability is not easily understood by those who control research funds.

5. NEFs Near a Stagnation Point

The problem is sketched in figure 3. The velocity field is

$$v = \varepsilon(x,-y), \tag{33}$$

where ε is the rate of strain, so that equations (30,31) have solutions for which T and h are functions of y only. The combustion field can be stratified with the flame flat, as for an SVF. If the flame sheet is located at

$$y = y_*, \tag{34}$$

then

$$W = \varepsilon y_*,\ \kappa = 0,\ \ v_\perp = \varepsilon x, \tag{35}$$

and the Karlovitz stretch

$$K = \partial(\varepsilon x)/\partial x = \varepsilon \tag{36}$$

is just the strain rate.

If the wall $y = 0$ is a thermal insulator, or there is an identical opposing jet in $y < 0$, the boundary condition

$$\partial h/\partial y = 0 \quad \text{at} \quad y = 0 \tag{37}$$

must be applied. (The leading-order temperature (31a) satisfies the corresponding condition automatically.) The requirement (37) is also satisfied when the flow is uniform, the flame being then plane with reaction zone at $y = y_*$. The only role of the wall is to change the uniform flow into one that stretches the flame; heat-loss effects because of this geometrical role are prevented by the condition (37).

Behind the flame sheet

$$d^2h/dy^2 + \varepsilon y\, dh/dy = 0, \tag{38}$$

so that

$$h = -T_b^2\phi_* \quad \text{for} \quad 0 < y < y_* \tag{39}$$

in view of the condition (37). Ahead of the flame sheet

$$d^2T/dy^2 + \varepsilon y dT/dy = 0,\ d^2h/dy^2 + \varepsilon y dh/dy = \ell\varepsilon dT/dy \text{ for } y_*<y<\infty \tag{40}$$

while

$$T \to T_f,\ h \to 0 \quad \text{as} \quad y \to \infty. \tag{41}$$

At the flame sheet itself, the jump conditions (27-29) require

$$T = T_b,\ h = -T_b^2\phi_*,\ \ dT/dy = -\ell^{-1}dh/dy = -Y_f e^{-\phi_*/2} \quad \text{at } y = y_* + 0. \tag{42}$$

The problem is therefore reduced to solving the differential equations (40) under the boundary conditions (41,42). Since there are six boundary

conditions on this fourth-order system, we may expect the parameters ϕ_* and y_* to be determined as functions of ε.

Independent solutions of the T-equation (40a) are 1 and erf(δy), where

$$\delta = (\varepsilon/2)^{\frac{1}{3}}; \tag{43}$$

the boundary conditions (41a), (42a) then show that

$$T = T_f + Y_f \operatorname{erfc}(\delta y)/\operatorname{erfc}(d) \text{ with } d = \delta y_*. \tag{44}$$

A particular solution of the h-equation (40b) is now found proportional to $y\exp(-\delta^2y^2)$, from which we construct the solution

$$h = -T_b^2\phi_*\operatorname{erfc}(\delta y)/\operatorname{erfc}(d)$$
$$+ \ell Y_f[\delta y e^{-\delta^2y^2}\operatorname{erfc}(d) - de^{-d^2}\operatorname{erfc}(\delta y)]/\pi^{\frac{1}{2}}(\operatorname{erfc} d)^2 \tag{45}$$

satisfying the boundary conditions (41b),(42b). The relation

$$\phi_* = 2\{\ell n[\pi^{\frac{1}{2}}\operatorname{erfc}(d)/2\delta] + d^2\} \tag{46}$$

and, finally, the equation

$$\delta = (\pi^{\frac{1}{2}}/2)\operatorname{erfc}(d)\exp\{d^2 + [de^{-d^2}/\pi^{\frac{1}{2}}\operatorname{erfc}(d) - \tfrac{1}{2} - d^2]\bar{\ell}\} \text{ with } \bar{\ell} = Y_f\ell/2T_b^2, \tag{47}$$

for the standoff distance y_* as a function of ε, follow from the boundary conditions (42c,d).

Of greatest interest is the flame speed (35a) as a function of stretch (36), and this is plotted in figure 4 for various values of $\bar{\ell}$. As $\varepsilon \to 0$, W tends to the value 1 (that for an adiabatic plane flame). As ε

increases from zero, W initially decreases for $\bar{\ell} > -1$, but increases for $\bar{\ell} < -1$, in agreement with SVFs for $L \gtrless 1$. This behavior is described by the formula

$$W = 1-\varepsilon(1+\bar{\ell}) + O(\varepsilon^2), \tag{48}$$

which can be shown to hold quite generally for flows with small strain. (The formula has implications for stability, see section 5. .) Further increase in ε leads to two possibilities: for $\bar{\ell} < 2$, the flame sheet eventually moves to the wall and is extinguished; for $\bar{\ell} > 2$, extinction takes place in the interior of the flow.

In short, stretch usually decelerates the flame and always extinguishes it. Acceleration will occur for weak stretch if the Lewis number is sufficiently far below 1.

Success in treating stagnation-point flow is due to the reduction from partial to (tractable) ordinary differential equations that is effected by the velocity field (33); changing the boundary conditions makes no difference, provided they are independent of x. For example, Buckmaster and Mikolaitis have replaced the wall by an inert counterflow at a temperature close to T_b, and Daneshyar, Ludford, & Mendes-Lopes (1983) have considered loss of heat to the wall. Daneshyar, Ludford, Mendes-Lopes, & Tromans (1983) have even taken account of expansion through the flame by modifying the velocity field without losing tractability. Finally, Mikoalitis & Buckmaster (1981) have considered rear stagnation-point flow (i.e. $\varepsilon < 0$); see section 7.6.

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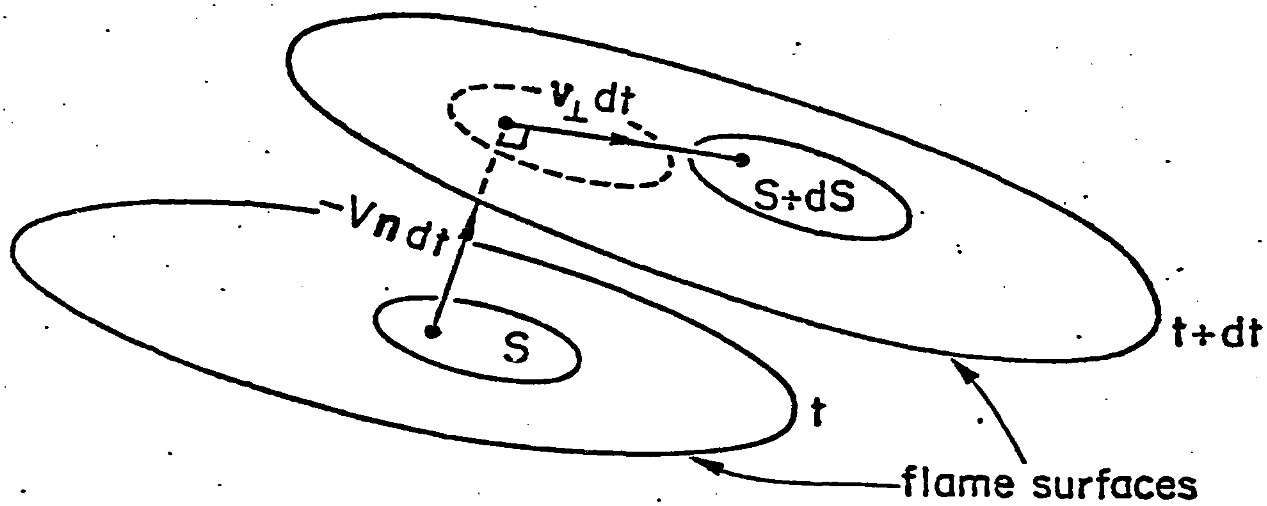
Figure Captions



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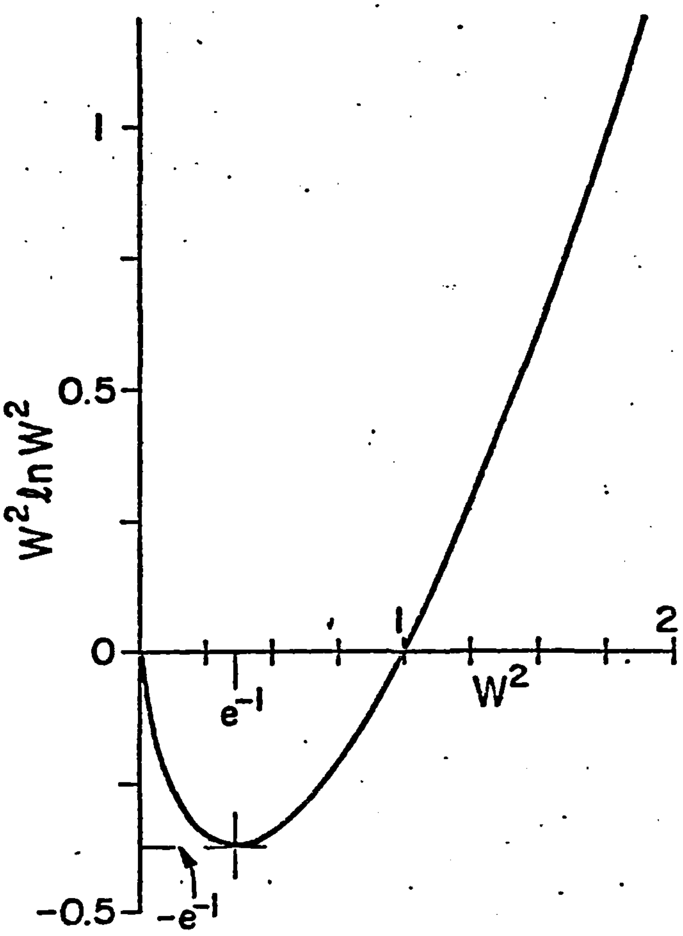

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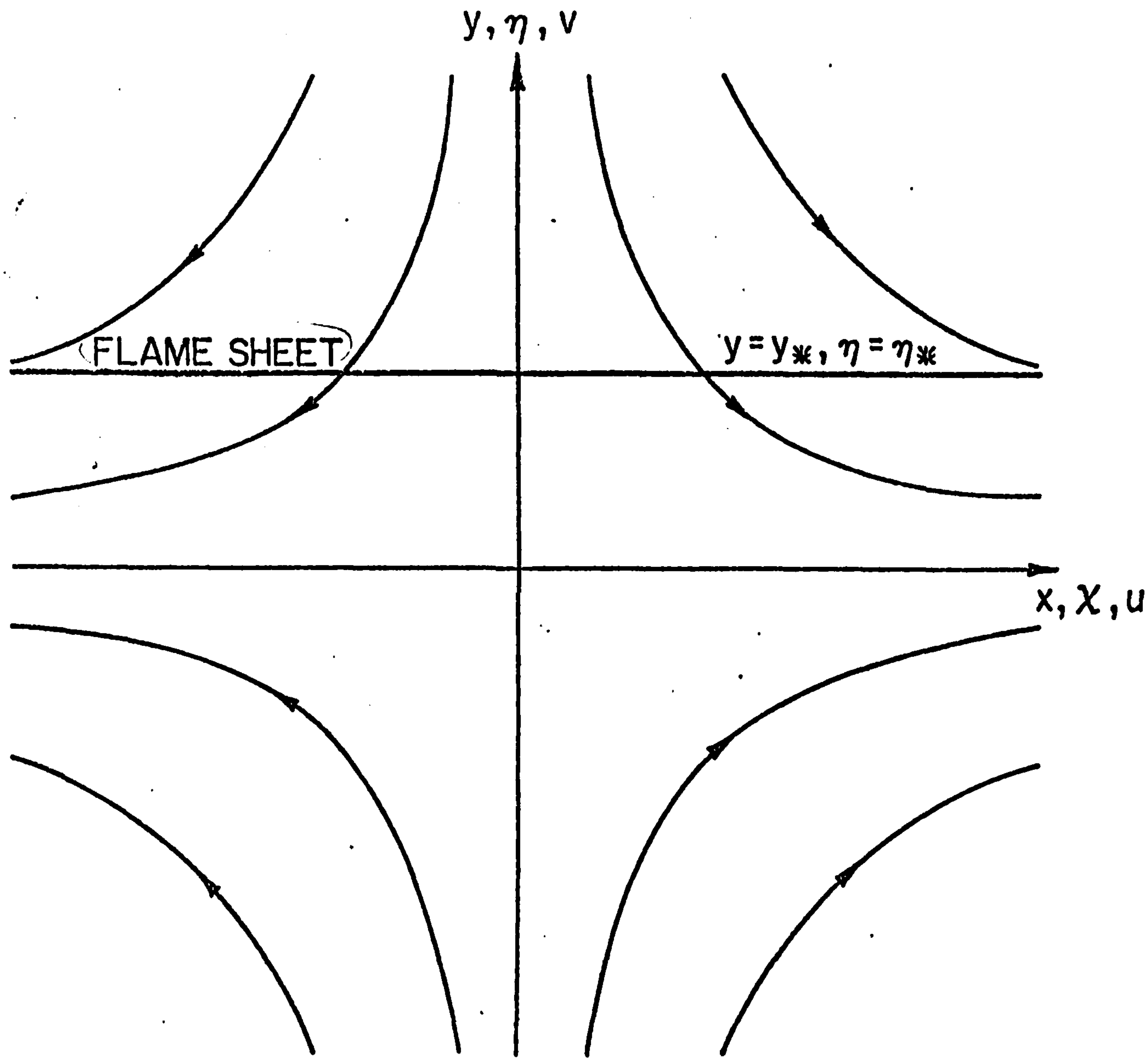

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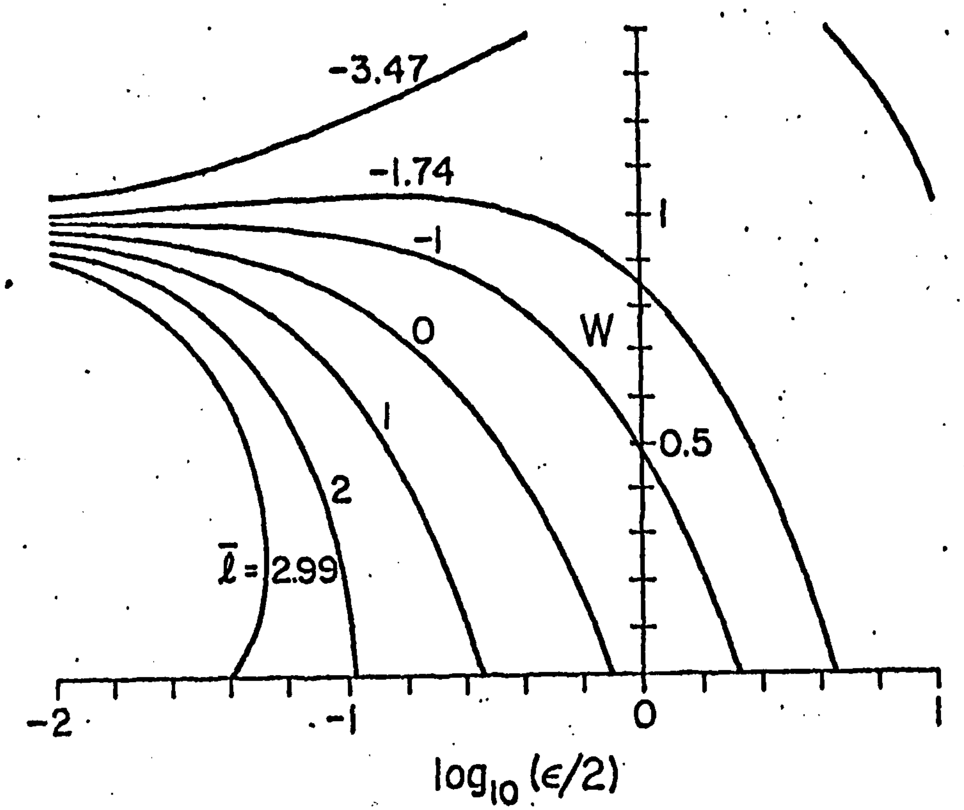

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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~~We shall~~ start by discussing this concept, so as to have it available when they ~~we~~ come to discussing general slowly varying and near-equidiffusional flames.